

Non-thermal Emission in Sagittarius B?

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ABSTRACT

We summarize three recent publications which suggest that the Galactic center region Sagittarius B (Sgr B) may contain non-thermal radio components (Crocker et al. 2007, Hollis et al. 2007 and Yusef-Zadeh et al. 2007a). Based on new VLA matched-resolution continuum data at 327 MHz and 1.4 GHz, we find no evidence for large scale non-thermal radio emission at these frequencies; the spectral behavior is likely determined by the complex summation of multiple HII region components with a wide range of emission measures and hence radio turn-over frequencies. Also, we discuss a possible additional interpretation of the radio continuum spectrum of individual component Sgr B2-F carried out by Yusef-Zadeh et al; confusion from nearby HII components with widely different turn-over frequencies may contribute to the the change in slope of the radio continuum in this direction at low frequencies. Finally, we discuss the uncertainties in the determination of the spectral index of the GBT continuum data of Sgr B carried out by Hollis et al. We find that the apparent spectral index determined by their procedure is also likely due to a summation over the many diverse thermal components in this direction.

1. Introduction

The radio spectrum of the Galactic Center (GC) has been a longstanding and complicated problem for astronomers. The GC radio source was slowly recognized to be a complex of individual

sources embedded in diffuse Galactic background emission. By 1965, when Bernard Burke’s review article, entitled ”Radio Radiation from the Galactic Nuclear Environment”, appeared in the *Annual Review of Astronomy and Astrophysics*, images of the GC region had been made at a range of frequencies as high as 14 GHz. One of the images in this review article was from Cooper & Price (1964), made with the Parkes, Australia, 210-foot telescope at 3 GHz. This image had a resolution of $6.7'$, making it possible to resolve the Sagittarius B (Sgr B) complex from the other major GC sources. Cooper & Price (1964) were the first to suggest that the Sgr B source is an optically-thick thermal source based on a spectral index measurement between 3 and 8 GHz (Drake 1959a,b) that had large uncertainties. During the last 40 years, the Sgr B region has been the subject of numerous detailed studies carried out with the increasing resolution and sensitivity of new instrumentation.

1.1. The SgrB Region: Sgr B2 and Sgr B1

The Sgr B region is now understood to be one of the most complex star-forming regions in the Galaxy. Located at ~ 105 pc in projection from Sgr A*, the Sgr B giant molecular cloud has a total mass of $8\text{--}20 \times 10^6 M_{\odot}$ (Tsuboi et al. 1999). Therefore, many interstellar molecules have been detected for the first time in the Sgr B cloud. Most studies of Sgr B have been carried out in the far-infrared and radio regimes because this region of the Galaxy is highly obscured (by up to 50 magnitudes) at visible wavelengths.

The Sgr B region is comprised of two distinct complexes: Sgr B2 (G0.7-0.0; to the North) and Sgr B1 (G0.5-0.0; to the South). Both sources are strong radio continuum sources and both have been well-studied on fine scales ($\sim 1''$ or better) with interferometric observations. In higher frequency radio observations ($\nu > 1.4$ GHz), Sgr B2 dominates due to the numerous ultra-compact, optically-thick HII regions (Benson & Johnston 1984; Gaume & Claussen 1990).

Sgr B2 is well-known for its incredibly high densities ($> 10^5 \text{ cm}^{-3}$) in both ionized and molecular gas (Huttemeister et al. 1993; DePree, Goss & Gaume 1998). The Sgr B2 complex has three bright cores - Sgr B2 “Main”, “North” and “South”. Sgr B2 shows radio emission over a factor of 6000 in size scale, from $< 1''$ (ultra-compact HII regions) to the $10'$ extent of diffuse emission along the complex. The highest resolution radio study of Sgr B2 was made at 43 GHz with the Very Large Array (VLA)¹ radio telescope with an angular resolution of ~ 64 milli-arcseconds (600 AU at the GC distance of 8 kpc) in SgrB2 Main. This study revealed over 20 ultra-compact HII regions and stellar wind sources in Sgr B2 Main alone (De Pree et al. 1998). In addition, the range of observed emission measures in the ionized gas are from 1×10^4 to $1 \times 10^9 \text{ pc cm}^{-6}$. Radio recombination line studies at numerous frequencies have helped cement the thermal nature of many of the individual radio components in the Sgr B complex (e.g., Mehringer et al. 1993). The radio emission arising

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from the Sgr B1 complex indicates that this region is a more highly evolved star-forming region with numerous filamentary and shell-like ionized structures (Mehring et al. 1992). Lying between Sgr B1 and Sgr B2 is a complex of radio sources known as G0.6-0.0. Gas velocities and morphology suggest that G0.6-0.0 physically connects Sgr B1 and Sgr B2 (Mehring et al. 1992).

1.2. Recent Papers: Non-thermal Emission in Sgr B?

Three recent papers on Sgr B complex have addressed the nature of the radio emission arising from this region, and have argued that there is a non-thermal component of the radio emission (Crocker et al. 2007; Hollis et al. 2007; and Yusef-Zadeh et al. 2007a). Because Sgr B is one of the most active regions of star formation in the Galaxy, containing more than 60 HII regions, it would not be surprising to find an embedded supernova remnant or two. However, because the preponderance of evidence for the last four decades has indicated that the Sgr B complex is a thermal radio source, claims of non-thermal emission deserve close scrutiny.

One of the main motivations for looking for non-thermal emission has come from high-energy investigations of this region. Using HESS, Aharonian et al. (1996) have made a detection of diffuse γ -ray flux between 0.2-20 TeV ($1 \text{ TeV} = 10^{12} \text{ eV}$) from the Galactic center (GC) region, distributed along the Galactic plane. In addition, a separate HESS measurement of the γ -ray flux and spectrum in a $0.5^\circ \times 0.5^\circ$ region was centered on the SgrB molecular cloud. After removal of several bright point-like sources, the diffuse flux is believed to be correlated with the density of molecular gas (H_2) in the GC region, which has been imaged in the CS ($J=1-0$) line transition (Tsuboi et al. 1999). One possible origin of the high-energy radiation is the collision between cosmic ray protons and the ambient, dense molecular gas in the GC. Crocker et al. (2007) predict the radio synchrotron spectrum from their broadband (radio to γ -ray) emission models and compare their results to the measured radio spectrum of this region. Crocker et al. (2007) base their radio spectrum of this region primarily on low-frequency data at 327 and 843 MHz (see below for a description). They determine that the radio spectrum of Sgr B is non-thermal in nature, with a measured excess of non-thermal emission.

In addition, Yusef-Zadeh et al. (2007a) consider the global heating of molecular clouds by cosmic rays, based on their earlier observations of correlations between molecular gas and 6.4 keV $\text{K}\alpha$ line emission (Yusef-Zadeh et al. 2007b). In order to illustrate that SgrB2 has a non-thermal component, Yusef-Zadeh et al. (2007a) use low frequency observations between 255 MHz and 1.4 GHz to show that a part of the SgrB2 complex (a well-studied part, SgrB2 “F”, a cluster of ultra-compact HII regions) has a component of non-thermal emission with a flux density of $\sim 82 \text{ mJy}$. They suggest the presence of enhanced heating by cosmic ray particles (which increases the ionization fraction) in the molecular gas.

Finally, Hollis et al. (2007) present a study of the continuum temperature of Sgr B2 based on GBT spectral line observations. They argue that there is a non-thermal component in Sgr B2 on

size scales of $\sim 143''$ at 1.4 GHz with an optically-thin spectral index of $\alpha = -0.7$.

In this paper, a discussion of the measurements used to derive the spectral index of radio emission in the above papers follows. In addition, a high-resolution 1.4 GHz image of the GC region is presented and used for comparison to the three recent results on the non-thermal emission in Sgr B.

2. Radio Observations of the Sgr B Region at Low Frequencies

2.1. 1.4 GHz VLA Image

Figure 1 shows a 1.4 GHz VLA image of the Sgr B region of the GC. This image was made using the DnC and CnB array configurations as part of an HI absorption study toward the central 250 pc of the Galaxy (e.g., Lang et al. (2003) and Lang et al. *in prep.*). In order to cover this large region, 5 fields were mosaicked together using the miriad task *mosmem*. The integration time was 8 hours for the set of five fields in each configuration (i.e., approximately 2.5 hours on each field) which resulted in an rms of 10 mJy beam^{-1} . The zero level in this image is within 1σ (10 mJy) of zero, and the image has also been corrected for the variable system temperature with frequency in the presence of HI emission. This mosaic is one of the highest-resolution images of the more extended structures in the complex GC region, with excellent sensitivity to both point-like and diffuse features. In this paper, this image is used to determine the flux density of the Sgr B complex and to help constrain the radio spectrum of Sgr B.

2.2. Flux Density of the Sgr B Complex at Low Frequencies

Based on data at 327 and 843 MHz, Crocker et al. (2007) determine that the radio emission arising from the Sgr B region is non-thermal. At 327 MHz, Crocker et al. (2007) use data from Brogan et al. (2003) smoothed from the original resolution of $120'' \times 60''$ to $252''$. They measure the integrated flux density in two regions: (1) the field of view of the HESS detection, which is a large region of $0.5^\circ \times 0.5^\circ$ size centered on Sgr B and (2) a smaller region containing primarily the bright radio emission associated with Sgr B1 and B2 radio sources. For the large region, they measure the flux density to be $45 \pm 10 \text{ Jy}$, and for the smaller region they measure 25 Jy. At 843 MHz (using an image from SUMSS; Bock et al. 1999), a two sigma detection of $20 \pm 10 \text{ Jy}$ for the $0.5^\circ \times 0.5^\circ$ region is obtained by Crocker et al. (2007). They also attempt to measure the flux density at 74 MHz in an image from Brogan et al. (2003), but they can not obtain a result for the flux density of this region. It is likely that the spectrum derived by Crocker et al. (2007) is not reliable due primarily to the poorly-determined flux density at 327 MHz, coupled with the poor signal-to-noise of the 843 MHz data. At 327 MHz, there are large distortions in the image due to missing flux and confusion from SgrA West and East. It is not possible to obtain an accurate flux

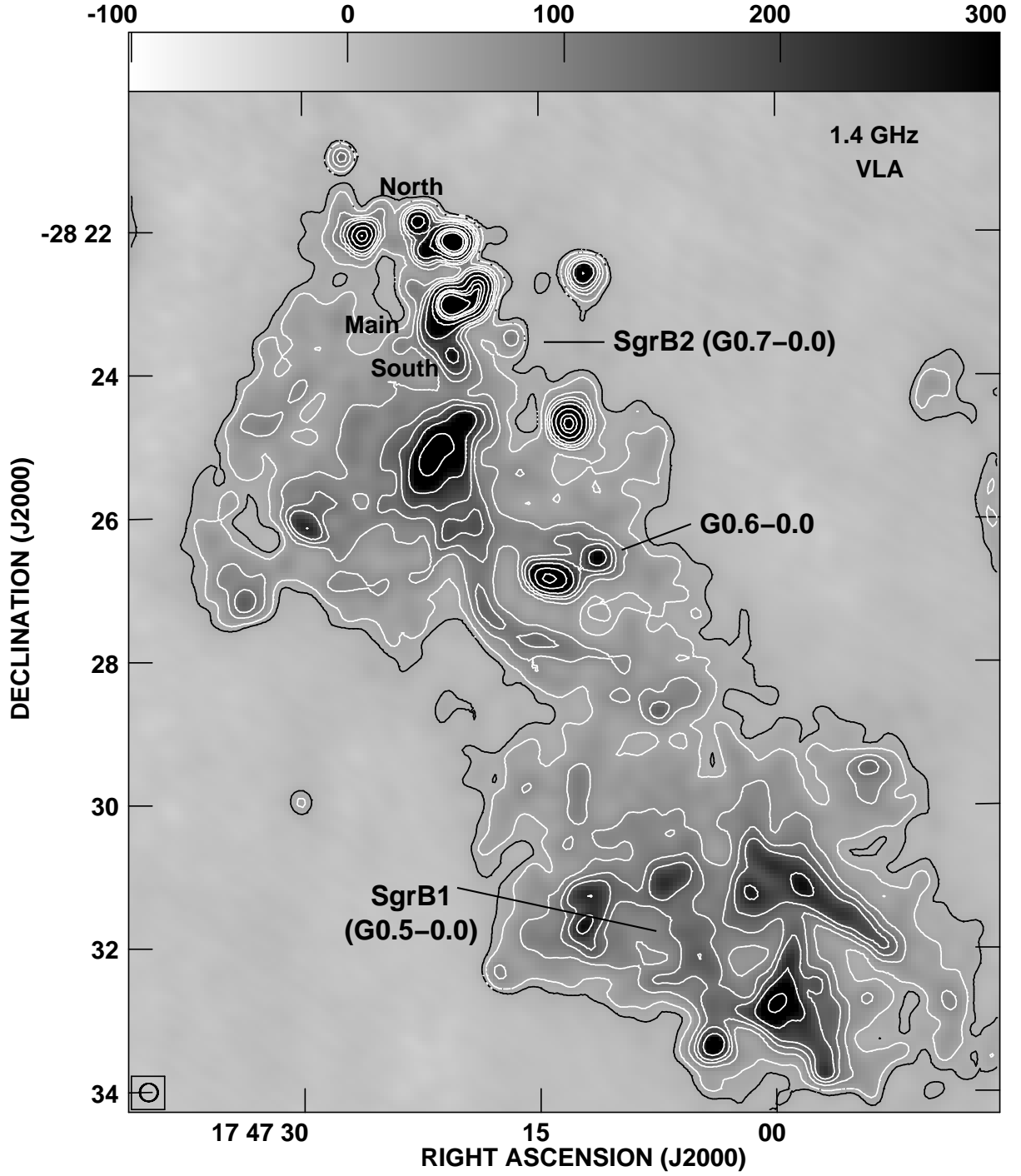


Fig. 1.— VLA 1.4 GHz continuum image of the SgrB1 and B2 region from Lang et al. (2003) and Lang et al. *in prep.*. The image has a spatial resolution of $15'' \times 15''$ and an rms level of 10 mJy beam^{-1} . Contours are at levels of 3, 5, 10, 15, 20, 30, 50, 90, 100, and 125 times the rms level.

density over a region as large as $\sim 0.5^\circ \times 0.5^\circ$.

We suggest that a more reliable radio spectrum can be determined by using VLA data at two frequencies (1.4 GHz and 327 MHz) with matched (u,v) coverage. Data from Brogan et al. (2003) were used at 327 MHz and at 1.4 GHz from Lang et al. (2003; also presented above). The flux densities were obtained over a region which includes the radio emission associated with Sgr B1 and B2 (up to an angular size of $\sim 0.3^\circ$), with careful consideration of the problems of the displacement of the zero level. At both frequencies, good signal-to-noise determinations are possible. We have used the AIPS task *IRING* to determine the flux in concentric rings. The total cumulative flux density can then be determined as a function of radius. The total flux density at 1.4 GHz over a region that includes both Sgr B1 and B2 is 83 ± 7 Jy with a radius of $500''$ ($8.3'$). For Sgr B1 and B2 individually, we determine separate flux densities at 1.4 GHz of 35 ± 5 Jy and 49 ± 6 Jy. At 327 MHz, we determine a flux density of 37 ± 7 Jy for Sgr B over a region of the same region used at 1.4 GHz.

In Table 1 we summarize the flux density determinations from this paper and compare these with Crocker et al. (2007) and previous VLA measurements. The agreement with Mehringer et al. (1993) is encouraging. In addition, the 327 MHz measurement for Sgr B2 of Yusef-Zadeh et al. (2007b) agrees well with our determination (see Table 1). Our results, which have high signal-to-noise and matched (u,v) coverage, provide good evidence that the flux density of the Sgr B complex *increases* from 327 MHz to 1.4 GHz, in contrast to the conclusion of Crocker et al. (2007). The current data are in good agreement with previous independent VLA studies (see Table 1 and Mehringer et al. 1992, 1993).

A likely explanation of the radio spectrum of Sgr B we derive (i.e., thermal) is the large halo of size $10' \times 5'$ first described by Mehringer et al. (1993). This halo represents a “transition” region from HII gas optically thick at 327 MHz becoming optically thin at the higher frequencies. In order to provide a crude estimate of the physical parameters of the halo, we estimate that $\sim 50\%$ of the emission at 1.4 GHz arises from the halo. This estimate is derived by summing all the compact components in Figure 1 (~ 40 Jy) and subtracting this from the total flux density of ~ 83 Jy (see Table 1) to obtain a flux density of ~ 40 Jy. For a source of radius ~ 15 pc, the emission measure is $1 \times 10^5 \text{ pc}^{-6}$, with an rms electron density of 60 cm^{-3} . The implied opacity in the continuum at 327 MHz is then $\tau \sim 0.3$ for a source of this size. Thus, the ratio of flux densities from 1.4 GHz to 327 MHz for the entire Sgr B complex is 2.2 and not the ratio for a source that is completely optically thick at both frequencies (which would be 21). This small ratio of flux densities (~ 2) is likely due to a very gradual turnover in the spectrum at these frequencies because of the wide range of emission measures across the Sgr B complex.

Finally, we note that Yusef-Zadeh et al. (2007a) determine that a small region within the Sgr B2 complex is non-thermal, Sgr B2-F. The cluster of ultra-compact HII regions known as Sgr B2-F has been studied at very high angular resolution and measures only several arcseconds across (DePree et al. 1996). Yusef-Zadeh et al. (2007a) suggest that the flux density at 255 MHz arising

from this region (Sgr B2-F) is enhanced due to a non-thermal contribution of this source. However, an alternative interpretation is that the excess flux density that Yusef-Zadeh et al. (2007a) measure at 255 MHz may be due to confusion from the numerous sources within the GMRT beam ($22''$). There are likely to be more than 25 compact sources within the $22''$ beam, based on Figures 2 and 4 in Gaume et al. (1995). For example, source Sgr B2-I lies only $\sim 4''$ to the E of Sgr B2-F and has a flux density in the range of 100-200 mJy at 1.375 MHz (Mehring et al. 1995). Some of these sources may well have lower density structures which will contribute to a complex distribution of opacities and emission measures within the GMRT beam, resulting in a slight deviation of the spectrum from the optically thick portion of the low frequency spectrum.

2.3. Continuum Temperature of Sgr B2

Hollis et al. (2007) noted that the Green Bank Telescope (GBT) continuum antenna temperature toward Sgr B2 is linear on a log-log plot. From this straightforward result, they carried out an analysis suggesting that the bulk of the emission from this direction is non-thermal and can be associated with a source of size $143''$ at 1 GHz, with a source size decreasing with frequency as $\nu^{-0.52}$. We examine their methods and results, and suggest some problems in their analysis. We address three points: the effect of source structure on the measured continuum temperature, the estimates of source size from archival VLA observations, and the question of the 43 GHz flux density from this region.

At their lowest frequency (1.35 GHz), the FWHM of the GBT beam is $9.1'$, while at their highest frequency (47.68 GHz) the FWHM is $16''$. Within a FWHM of $9.1'$, more than 100 components in the Sgr B2 complex are detected in high resolution images. The majority of these components are known to be thermal both because of their radio continuum spectra and because of the presence of recombination lines (Gaume & Claussen 1990, Mehringer et al. 1992, 1993). Emission measures of these components have a very wide range of values. Because the GBT beam scales as ν^{-1} , these components will contribute differently to the measured flux density due to their relative positions and to the changes in opacities because of the scaling of τ as $\sim \nu^{-2.1}$. Therefore, the apparent non-thermal spectral index ($\alpha = -0.7$) of the continuum temperature measured with the GBT by Hollis et al. (2007) may be due to integrating over the large number of components in Sgr B2. The opacities change with frequency and the contribution of each compact source varies systematically as the GBT beam size changes with frequency.

If the flux density of a point source were independent of frequency, then the procedure of Hollis et al. (2007) would yield a spectral index of zero. For an extended source (size \gg than the GBT beam), the measured flux density would scale as the beam area, i.e. as ν^{-2} . The measured flux density is proportional to the quantities plotted in Figures 1a, 1b, and 2a of Hollis et al. (2007) (with minor corrections for efficiencies). In their equation (3), a structure correction $(1 + \theta_s^2/\theta_b^2)$ is introduced to compensate for the resolution of the source. This correction would remove the ν^{-2} dependence that results from the beam area when $\theta_s^2/\theta_b^2 \gg 1$.

It is useful to demonstrate the effect of integration over a complex distribution. The 1.4 GHz image shown in Figure 1 is multiplied by the GBT beam pattern (approximated by a Gaussian with the same FWHM and positioned at the Hollis et al. (2007) pointing center) and summed to obtain the total flux density “observed”. This method can be carried out at a number of frequencies. This procedure then shows that an apparent spectral index can be caused by structure alone. If the flux density is plotted on a log-log plot against frequency, the result is linear with a slope of $-1.07 (+/- 0.05)$. This result may be compared with Hollis et al. Fig 1b of the continuum antenna temperature which has a slope of -1.06 . In view of the complicated structure of the source shown in the Sgr B2 complex in Figure 1, the approximation used by Hollis et al. to make the structure correction is clearly questionable. However, if we ignore this misgiving and the Hollis et al. (2007) structure correction were made, the slope would become -0.82 ± 0.08 . This value may be compared with Figure 2b of Hollis et al. (2007) in which the slope is given as -0.7 . While this is not a simulation because we use data at only one frequency, this demonstration convinces us that the effect of structure cannot be ignored when trying to interpret the GBT continuum temperature. In our opinion, the apparent non-thermal spectrum reported by Hollis et al. (2007) is an effect of source structure alone.

In addition, estimates of source size obtained by heavily tapering VLA data are not realistic. The most compact VLA configurations were used in all of the archival observations analyzed. The shortest spacings (measured in wavelengths) increase with frequency so that the largest angular scale observable decreases with increasing frequency. Therefore it is not surprising that the apparent source size decreases with increasing frequency. Typically, if VLA data has been tapered so that the beam size is increased by more than a factor of two to four, the imaging quality is too poor to be useful. Hollis et al. (2007) acknowledge that this effect may cause an unknown systematic uncertainty.

Finally, Hollis et al. (2007) indicate that their 43 GHz results are not consistent with the data of Mehringer & Menten (1997). The GBT pointing center is offset by more than $1/2$ the FWHM of the beam at 44 GHz from the centroid of the Sgr B2 N complex as shown in Figure 1 of Mehringer & Menten (1997). Therefore, the GBT would be expected to measure a lower flux density. The four highest frequency points in Figure 2 of Hollis et al. (2007) show a systematic decrease in flux density by a factor of ~ 1.6 . For a source beyond the half-power point of the beam, the flux density is expected to decrease rapidly with increasing frequency because of the simultaneous narrowing of the antenna beam. Therefore, because of the different pointing centers, the 43 GHz data of Mehringer & Menten (1997) and that of Hollis et al. (2007) may well be consistent.

In summary, the apparent non-thermal power law slope for the Sgr B2 continuum temperature observed by the GBT is likely determined by source structure and provides limited information about the physical processes in the Sgr B region.

2.4. Previous Studies of Non-thermal Emission in Sgr B

The three 2007 papers addressed above are not the first which have suggested a possible non-thermal component in the Sgr B region. For example, Reich et al (1987) compared images of Galactic center sources at $60\ \mu\text{m}$ and 2.6 GHz with a resolution of $6'$, and concluded that Sgr B2 was possibly non-thermal. Akabane et al. (1988) compared images at 43 and 10.7 GHz (convolved to $1.3'$) and suggested possible non-thermal emission in the southern part of Sgr B2. Akabane et al. (1988) also noted that their result may imply that each of their compact sources may consist of a complex of HII regions, some optically thick and some optically thin. Because of the source structure apparent in Figure 1 and the subsequent studies of Sgr B2 with higher angular resolution (DePree et al. 1996, 1998), we believe this suggestion is correct. Haynes et al. (1992) imaged the polarized emission near the GC with $\sim 2.8'$ resolution. While one of the arcs of polarized emission (major axis size of $\sim 0.8^\circ$) crosses Sgr B2, it would seem to be a part of the diffuse Galactic emission, not a part of Sgr B2.

3. Conclusions

In this paper, we have summarized three recent papers which point out possible non-thermal radio emission arising from the Sgr B region in the GC. We also present a high-resolution and sensitive VLA image of the Sgr B region at 1.4 GHz. Using this image and a matched-array 327 MHz VLA image, we derive a thermal spectrum for the Sgr B complex and suggest that the radio emission is a mixture of optically thin and optically thick emission over the frequency range discussed here (255 MHz to 1.4 GHz). In addition, we show that the the apparent non-thermal power law slope for the Sgr B2 continuum temperature observed by the GBT is likely determined by source structure and provides limited information about the physical processes in the Sgr B region. While the structure Sgr B region is complex and furthermore confused by the Galactic background, there does not appear to be substantial evidence for a non-thermal component in the Sgr B complex.

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Table 1. Radio Flux Density of the Sgr B Complex

Frequency (GHz)	VLA Array(s)	Spatial Resolution	Sgr B (Jy)	Sgr B1 (Jy)	Sgr B2 (Jy)	Reference
1.4	DnC,CnB	$15'' \times 15''$	83 ± 7	35 ± 5	$49 \pm 6^*$	This paper
1.4	D,C	$26'' \times 15''$	75	26	39*	Mehring et al. (1993)
0.843	—		$20 \pm 10^{**}$	—	—	Crocker et al. (2007) [‡]
0.327	C,D	$60'' \times 120''$	37 ± 7	—	17 ± 4	This paper [†]
0.327	B,C,D	$41.6'' \times 22.7''$	—	—	17	Yusef-Zadeh et al. (2007b)
0.327	C,D	$252'' \times 252''$	$45 \pm 10^{**}$	—	—	Crocker et al. (2007) [†]

*Sgr B2 region includes emission from the G0.6-0.0 complex.

**Flux density is for the HESS large region of size $0.5^\circ \times 0.5^\circ$.

[†]Data from Brogan et al. (2003).

[‡]Data from Bock et al. (1999).